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A METHOD FOR IMPROVING NIGHT VISION DEVICE DEPTH OF FIELD (U)

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

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It is known that when using Night Vision Devices (NVDs) to view objects close to the observer, the depth of field, the volume of space that appears to be in focus, is extremely small. The depth of field of optical systems can be increased by slowing the system's f-number. A simple way to accomplish this is to add restrictive apertures onto the front of the objective lens. This noticeably increases NVD depth of field but causes a significant reduction in light gathering capability. This report addresses equations describing the phenomenon, assesses the tradeoffs that we are involved in using apertures to increase depth of field, and documents some experimental visual acuity data demonstrating an increased depth of field due to decreased lens aperture.

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PREFACE

The work described in this technical report was funded under Program Element 62202F, Project 7184-18-07 entitled "Night Vision Technology" and Program Element 63231F, Project 3257, entitled "Helmet-Mounted System Technology" (HMST). The primary purpose for this report is to document a theoretical examination to a particular approach for increasing night vision device (NVD) depth of field. This work was the result of a request from Headquarters Joint Special Operations Command (HQ JSOC) for improved methods of identifying targets through NVDs at close range, well inside the hyperfocal distance of an infinity focused NVD. This report is a theoretical treatment of the subject to first order only. Certain assumptions and approximations, considered beyond the scope of this report, might strongly influence the equations derived here.

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INTRODUCTION

An on-going problem with Night Vision Devices (NVDs) is the devices' depth of field which is determined by the NVD optics. When the device is focused far away, such as at infinity, objects close in are out of focus. This problem has little effect on pilots flying an aircraft, whose attention is on distant objects, but it presents a safety hazard for some crewmembers who must constantly move about the aircraft, refocusing their NVDs while trying to accomplish complicated tasks (Donohue-Perry, et. al., 1993). When focused close to the user, NVD depth of field is extremely small. If a user moves their head only a few inches, the image moves in and out of focus quite rapidly, complicating their tasks.

Over the years, users developed unique procedures to overcome this device shortfall. Constant refocusing of the device may be unacceptable to the user who frequently changes the point of their attention, such as a load master, gunner, or medic (Donohue-Perry, et. al., 1992). Users may also be unable to refocus their devices because of their workload or for other reasons (Donohue-Perry, et. al., 1992). Focusing the two channels of the NVD at two different points, one near and one at infinity, was a quick but unofficial way to partially overcome the problem. Refusing to refocus and working with an out of focus image was another possibility for some users. But these approaches unknowingly created a hazardous work environment, producing severe visual rivalry problems, resulting in physical and mental discomfort. (Donohue-Perry, et. al., 1992) These quick solutions never fully nor satisfactorily solved the problem.

Fortunately, improvements can be made if the user is willing to accept certain tradeoffs. Several methods for improving NVD depth of field by modifying the imaging optics are possible. This report examines one approach, involving reducing the objective lens f-number (f/#) by using small apertures, and its nuances that potentially limit NVD performance.

CONCEPT

All imaging systems have a maximum resolution or highest spatial frequency the system can process. Usually this is determined by the modulation transfer function (MTF) of the imaging system optics. In the case of NVDs, the maximum resolution is limited by the image intensifier tube (I^2) microchannel plate under high light conditions and by the human eye under low light (Csorba, 1985). If an imaging system is used to view a target made up of white and black bars, low line frequencies made up of wide bar patterns, or low spatial frequencies, will be seen by the user of such a system as sharply focused high contrast bars. Higher spatial frequency patterns, made up of thin bars, will appear smeared or gray to the observer. This sets the smallest object size or more importantly, the smallest image size the device can produce. This is largely determined by the imaging array or the I^2 tube in the case of NVDs.

This smallest image size is important because it sets the limit on the acceptable amount of defocus, or blur size. This report concentrates on the high light condition where the NVD is microchannel-plate-limited. Treatment of the problem changes somewhat when the system is eyeball limited and will not be addressed here. Depth of field arises from the ability of an imaging device to accept defocus (Jenkins & White, 1978). From Figure 1, the lens shown is focused on a point, F, some distance away and places a perfect point image, F', on the imaging array at a distance s'. Note that imaging systems have some factor in them that limits the size of images they can process. Common limits are the detector picture element size or the aberration spot size of the objective or eyepiece lens. Because of these limits, the imaging system cannot process points that create image sizes smaller than the minimum blur size, B. A point image will appear to be as large as B to the imaging system. At the same time, there are other points in the system's field of view that are displaced longitudinally by some distance, from the point on which the imager is focused, such as points y and z in Figure 1. Light from these other points is captured by the imaging lens and focused somewhere behind it depending on how far away they are. The only place where these images can form is the imaging array, which is not at an optimum location for these other points. Therefore, these images are slightly defocused. It is possible that the images from some points form near enough to the photocathode to have blur sizes of B or less on the imaging array and appear to be in focus to the device. Since the imager cannot tell the difference between an image of a point focused to smaller than B and a defocused image of a point whose diameter is equal to spot size B, they both appear the same when processed. This creates a range of objects that the observer can see "perfectly" without needing to refocus, giving rise to the device's depth of field.

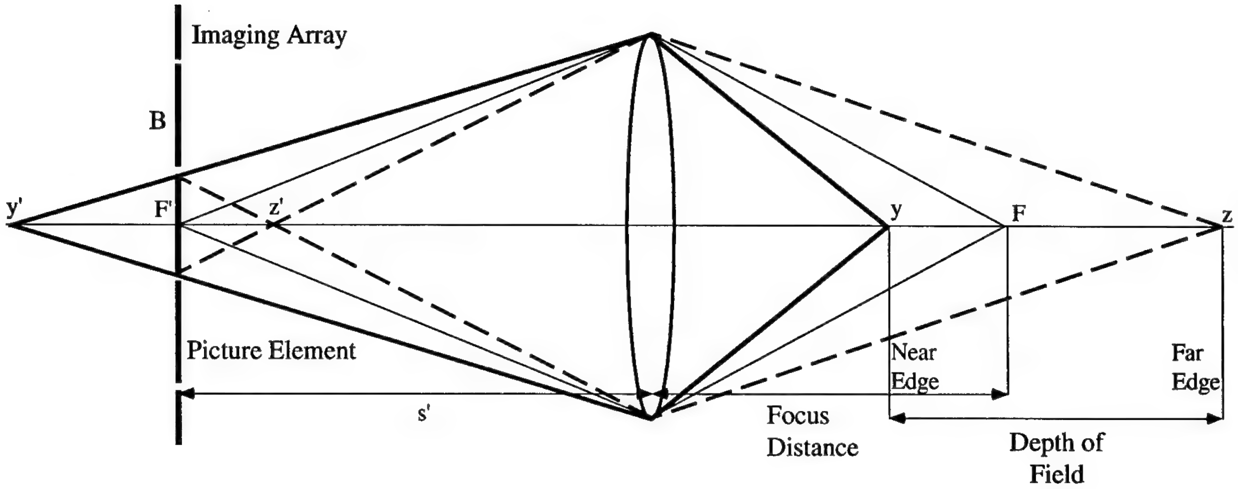

Figure 1. Basic depth of field geometry.

There are several interpretations of what sets the minimum spot size for an imaging system. The theoretical limit is the size of each picture element in the array, or the pixel size. For I^2 tubes, this pixel size is the center-to-center spacing of the holes in the microchannel plate (Csorba, 1985). But, from a more practical point of view, the smallest spot size is set by the maximum resolution of the entire optical system, which includes the human observer. This raises numerous questions about NVD depth of field when the system is human vision limited, such as in low light level and low contrast conditions, and not device limited, as it is in high light conditions. Depth of field will be different in low light and low contrast conditions.

Figure 1 indicates that, because of the geometric nature, or ray nature, of light, the lens diameter influences the rate at which the rays converge. Large diameter lenses force light rays to converge more quickly and with steeper slope than small diameter lenses of the same focal length. A traditional way to quantify this ray convergence rate is lens f/# which can be expressed mathematically (Jenkins & White, 1978):

$$f/\# = \frac{f_o}{D} \tag{1.1}$$

In this equation f_o is the lens focal length and D is the lens diameter. Numerically small f/# lenses, or fast lenses, force light rays to converge more rapidly than numerically larger ones, or slow lenses. NVD objective lenses are fast lenses, such as f/1.23 of the Aviator's Night Vision Imaging System (ANVIS) (MIL-L-49426(CR)), which maximizes their light gathering capability.

This rate of ray convergence influences the blur size of defocused images. Slowing down the lens f/#, decreasing the rate at which the rays converge, decreases the blur size of images on the

imaging array for points a given distance from the imaging system. Decreasing the blur size of the images allows defocused images farther from the imaging array to appear in focus. This in turn increases the device depth of field. Unfortunately, for fast NVD objective lenses, the opposite is also true. Fast lenses cause light rays to converge quickly, making blur sizes geometrically larger, narrowing the range of images that appear in focus to the detector array, resulting in a small depth of field. Therefore, slowing lens f/# will increase imaging device depth of field. Equation 1.1 indicates that lens f/# can be slowed by decreasing the lens diameter. This can be accomplished by masking off parts of the lens with external apertures.

Please note that there are several approximations involved in this treatment. NVD objective lenses are complex, multi-element devices, approximated here by a single lens. The cone of light out of the objective lens appears, to the photocathode, to come not from the front of the objective lens but from the lens' rear principle plane. This plane is somewhere within the lens itself for an NVD. To control this cone of light the apertures should be placed in the objective lens' aperture stop. However, this cannot be done because the aperture stop also falls somewhere inside the NVD. Therefore, the equations derived in this report are not exact and may not fully explain nor predict some depth of field phenomena.

DERIVATIONS

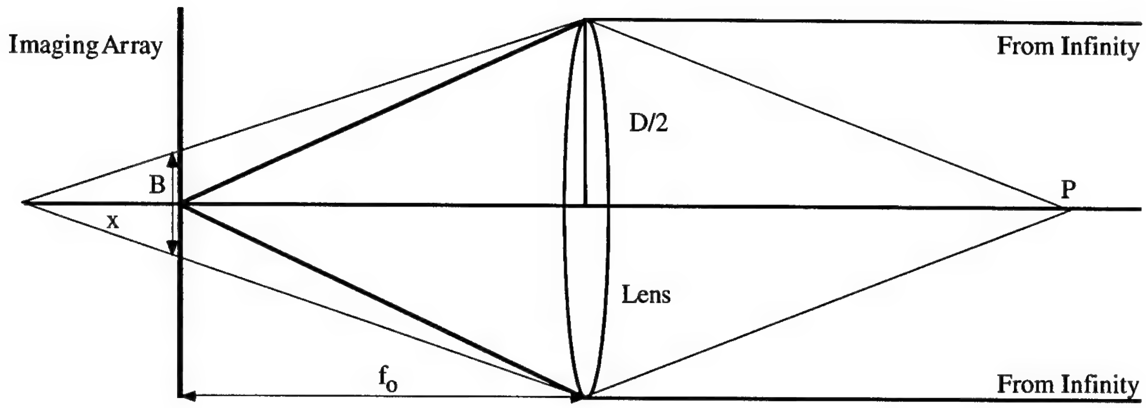

Figure 2. Geometry for derivation of hyperfocal distance equation.

Hyperfocal Distance

One should note that imaging system objective lenses are normally not single lenses but rather complex combinations of glass and plastic lens elements. For these complex lenses, the focal length of the lens, f_o, is the distance from the rear principle plane to the focal plane. To simplify the diagrams and to make the geometry more clear, complex objective lenses will be represented by a simple, single lens element. Take, for example, a lens focused at infinity, such as in Figure 2.

An interesting condition can be derived from the geometry of Figure 2. Because it is focused at infinity, we know that the distance from the lens to the imaging array is exactly f_o. (Jenkins & White, 1976) We also know that because of the acceptable blur size, B, some points closer to the observer than infinity will be in acceptable focus. From this information, it is possible to determine the distance to the closest point that will appear in focus to an infinity focused imaging system. From Figure 2 a point inside infinity, P, that forms a blur circle of exactly B (appearing in focus to the imaging device) forms an image a distance x behind the photocathode. Given a lens of diameter D and a blur size B, x can be found by using basic geometry.

$$\frac{B/2}{x} = \frac{D/2}{f_o+x} \tag{2.1}$$

Therefore:

$$x = \frac{Bf_o}{(D-B)} \tag{2.2}$$

Once x is known, the near edge of the depth of field for an infinity focused lens can be found by determining the plane in object space that is conjugate to a distance ($f_o + x$) behind the objective lens. This can be calculated by using the thin lens equation (Jenkins & White, 1978):

$$\frac{1}{s} + \frac{1}{s'} = \frac{1}{f_o} \tag{2.3}$$

Here, s is the distance from the lens to the object and s' is the distance from the lens to the image. For this derivation, s' is equal to $f_o + x$. Substituting this into the thin lens equation yields:

$$\frac{1}{s} + \frac{1}{f_o+x} = \frac{1}{f_o} \tag{2.4}$$

Solving for s yields:

$$s = \frac{f_o(f_o+x)}{x} \tag{2.5}$$

Substituting the expression for x, Equation 2.2, into Equation 2.5 and simplifying yields an expression for the lens-to-object distance of:

$$HFD = s = \frac{f_o D}{B} \tag{2.6}$$

where HFD is the hyperfocal distance. This distance is the distance beyond which everything is in focus for an infinity focused lens. In this case, the depth of field corresponds to all distances greater than the hyperfocal distance. Note that the HFD is directly proportional to the diameter of the lens. Therefore, reducing the objective lens diameter will yield a desirably shorter HFD, and a longer depth of field. Also note that HFD is inversely proportional to blur size. A larger allowable blur size will lead to shorter HFD. This is a significant tradeoff because allowing a larger blur size lowers system resolution.

Depth of Field

Calculating HFD is not the best way to determine the largest potential NVD depth of field. Since the device in the previous derivation is already focused on infinity, it only exhibits a near side to its depth of field. There can be no far side to the depth of field when focused at infinity since it is impossible to have real objects farther away than infinity. Conceptually, this focus

condition only uses part of the viewing devices potential depth of field. When the device is focused well inside infinity, both near and far sides to the depth of field exist. Derivation of the equations locating the near and far edges of the depth of field is more involved than the one for HFD.

Figure 3 shows the geometry involved. The lens in the diagram is focused on an object at some distance, placing a sharp image on the imaging array. Points closer to the observer than the object on which the device is focused and whose images are at the threshold for acceptable blur, thus appearing well focused, image to a plane a distance y' behind the array. Note that the imaging array is opaque so there really is no image some distance y' behind it. Objects beyond the plane on which the device is focused form an image at a plane some distance in front of the imaging array. Since there is no surface on which images can form, the light rays continue to propagate until they are incident on the array, forming defocused blur circles. Those that form circles equal to the acceptable blur size form an image a distance z' in front of the imaging array. Images that form anywhere up to a distance y' behind or a distance z' in front of the imaging array will appear in sharp focus to the observer. The longitudinal distance in object space from which these images come is the device depth of field, as seen in Figure 1.

Two equations must now be derived, one for the depth of field's near edge and one for its far edge. The derivations are fairly similar and could be explained concurrently, but will be explained separately for clarity.

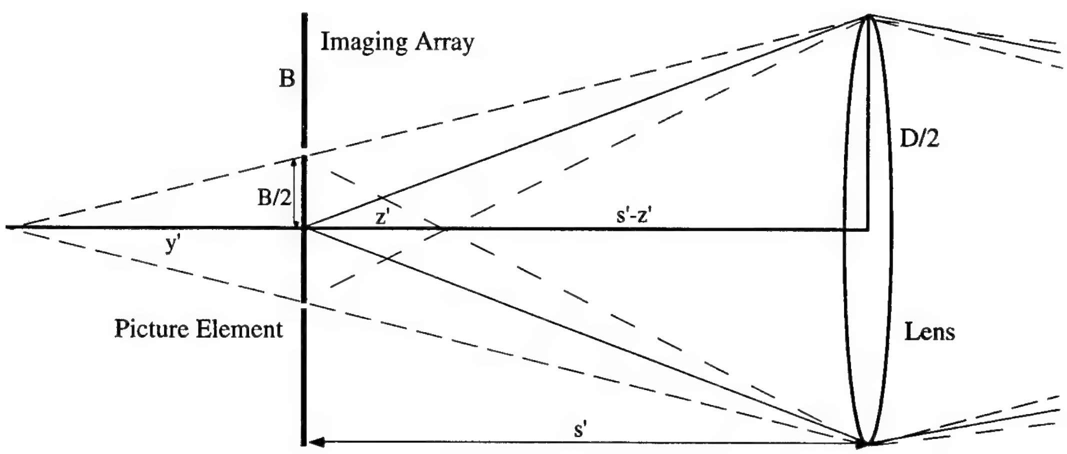

Figure 3. Geometry for derivation of equations describing depth of field boundaries.

Depth of Field - Near Edge

Objects closer to the imaging system than the plane on which the imaging system is focused will form images behind the imaging array. Point objects closer to the observer than the focus

distance that create blur circles with a diameter of exactly B will image a distance y' behind the imaging array. Referring to Figure 3 and using the similar triangles approach, it can be seen that:

$$\frac{B/2}{y'} = \frac{D/2}{s'+y'} \tag{2.7}$$

And therefore:

$$y' = \frac{Bs'}{(D-B)} \tag{2.8}$$

Remember that s' is the distance from the lens to the image for a given object distance. This can be found using the thin lens equation, Equation 2.3. Given that the lens, of focal length f_o, is focused on an object a distance f_d away, s' is:

$$\frac{1}{f_d} + \frac{1}{s'} = \frac{1}{f_o} \tag{2.9}$$

Solving Equation 2.9 for s' yields:

$$s' = \frac{f_o f_d}{f_d - f_o} \tag{2.10}$$

Now, the location of objects that image to the plane y behind the imaging array must be determined. Rewriting the thin lens equation so that S' is the image distance and S is the object distance gives:

$$\frac{1}{S} + \frac{1}{S'} = \frac{1}{f_o} \tag{2.11}$$

Solving for the object distance, S, gives:

$$S = \frac{f_o S'}{S' - f_o} \tag{2.12}$$

It is known that S' is equal to the image distance created by the lens for a chosen focus, s', plus the extra distance behind the imaging array at which acceptable images would form, y'. Therefore:

$$S' = s' + y' \tag{2.13}$$

Substituting Equation 2.13 into Equation 2.12 yields:

$$S = \frac{f_o(s'+y')}{(s'+y')-f_o} \tag{2.14}$$

Substituting Equation 2.8 for y' into Equation 2.14 and simplifying yields:

$$S = \frac{f_oDs'}{s'D-f_oD+f_oB} \tag{2.15}$$

Substituting Equation 2.10 for s' and simplifying yields the equation for the near side of the depth of field.

$$S = DOF_N = \frac{f_of_dD}{f_o(D-B)+f_dB} \tag{2.16}$$

Remember that f_o is the focal length of the objective lens, f_d is the distance at which device focus is optimized (or the chosen focus) D is the diameter of the objective lens (or the aperture restricting it) and B is the allowable blur size.

Depth of Field - Far Edge

The derivation of the equation for the far edge of the depth of field closely follows the one for the near edge. Objects farther from the imaging system than the plane of best focus will come into focus in front of the photocathode. Those whose point objects create blur circles of exactly diameter B form images a distance z' in front of the photocathode. Using geometry it can be seen that:

$$\frac{B/2}{z'} = \frac{D/2}{s'-z'} \tag{2.17}$$

And therefore:

$$z' = \frac{Bs'}{(D+B)} \tag{2.18}$$

Now the location of the objects forming these images must be determined. This distance can be found by applying the thin lens equation again, which again simplifies to Equation 2.12,

$$S = \frac{f_oS'}{S'-f_o} \tag{2.19}$$

However, S' now becomes:

$$S' = s' - z' \tag{2.20}$$

Combining Equations 2.18, 2.19, and 2.20 then simplifying yields:

$$S = \frac{f_o D s'}{s'D - f_o D - f_o B} \tag{2.21}$$

Substituting in Equation 2.10 for s', as was done in the derivation of the near edge of the depth of field, and simplifying yields the equation for the far edge of the depth of field, DOF_F.

$$S = DOF_F = \frac{f_o f_d D}{f_o(D+B) - f_d B} \tag{2.22}$$

One should notice that the equation for the far edges of the depth of field can generate negative numbers if f_d gets large enough, implying that DOF_F is beyond infinity. These results should simply be ignored since in the real world, distances cannot be negative and objects cannot be located farther away than infinity. Negative DOF_F values should be treated as an infinity result.

Limits

Notice what happens to the near edge of the depth of field when focus goes to infinity. To determine this mathematically, take the limit of the DOF_N equation, Equation 2.16, as f_d gets very large.

$$\lim_{f_d \to \infty} \frac{f_o f_d D}{f_o(D-B) + f_d B} = \frac{f_o D}{B} \tag{2.23}$$

This shows that for large f_d,

$$DOF_N = HFD = \frac{f_o D}{B} \tag{2.24}$$

When the imaging system lens is focused at true infinity, the near edge of the depth of field should converge to the system's hyperfocal distance.

Another important condition to note is the focus distance, f_d, at which the far edge of the depth of field goes to infinity. Mathematically, this happens when the denominator of Equation 2.22 goes to zero.

$$f_o(D+B)-f_dB = 0 \tag{2.25}$$

Solving for f_d yields:

$$f_d = \frac{f_o(D+B)}{B} \approx \frac{f_oD}{B} \tag{2.26}$$

Since D is much larger than B, this is essentially the hyperfocal distance. Therefore, when the imaging device's objective lens is focused at the device's HFD, the depth of field's far edge extends approximately to infinity. This is significant because depth of field asymmetrically surrounds the point of focus. If the device is focused at the HFD, then the near edge of its depth of field falls closer to the observer than the HFD. When this is combined with the fact that the depth of field's far edge extends to infinity for this particular focus condition, the maximum depth of field condition arises.

To quantify the maximum depth of field, the near edge must be located. By substituting Equation 2.26 into the equation for the near edge of the depth of field, Equation 2.16 and simplifying, its position can be determined. Equation 2.27 is the result of this simplification.

$$DOF_N = \frac{f_o(D+B)}{2B} \tag{2.27}$$

$$DOF_N \approx \frac{f_oD}{2B} \tag{2.28}$$

$$DOF_N = \frac{HFD}{2} \tag{2.29}$$

Note that this is approximately one-half the HFD (Equations 2.28 and 2.29). So, if the device is focused at the HFD, the depth of field extends from one-half the HFD to infinity. Since DOF_N slowly converges to the HFD as f_d gets larger, focusing at the distance described in Equation 2.26 will maximize device depth of field. Since objects cannot be located beyond infinity, this is the maximum depth of field for a particular imaging system. Focusing an NVD in any other plane will yield a smaller depth of field.

Infinity, or distances that are infinitely large are purely theoretical concepts. Objects a great distance away, such as stars, can still be pushed further away and therefore are not at infinity. But, optically, objects can be far enough away as to appear to the imaging system to be at infinity. If moving an object further away from the imaging system causes a negligible change in the image distance, the object is considered to be at infinity.

AN EXAMPLE

Example calculations are helpful in emphasizing the significance of these equations. The Air Force has acquired ITT's Model F4949 NVG, a variation of the AN/AVS-6 ANVIS. It is, therefore, appropriate to use it for the following calculations. Since the objective lens optical design is the same as the standard AN/AVS-6, many of the important parameters can be taken from the appropriate military specifications. The F4949 has an objective lens focal length of 27.03 mm and an f/# of 1.23 (MIL-L-49426(CR)). From this, its exit pupil diameter can be calculated to be 21.98 mm, using Equation 1.1. It has a specified maximum resolution of 1.0 cycles per milliradian (MIL-I-49428(CR)) which can be used to determining blur circle size. To convert maximum resolution to blur circle size, apply the following equation.

$$B = f_o \, \mathrm{Tan}(1/(2000 \, \mathrm{RES})) \tag{3.1}$$

In Equation 3.1, RES is the maximum resolution in cycles per milliradian, f_o is the objective lens focal length, and B is the blur circle size. Substituting the appropriate values into Equation 3.1 yields a blur size, B, of 0.01352 mm.

Now, recall Equation 2.6, the equation for the hyperfocal distance.

$$\mathrm{HFD} = \frac{f_o D}{B} \tag{3.2}$$

For the F4949, f_o = 27.03 mm, D = 21.98 mm, and B = 0.01352 mm. Applying Equation 3.2 yields a HFD of 43.56 m. Objects must be further than 43.56 m from an observer using an F4949 to appear to be at optical infinity. It should be noted that this particular NVD normally exhibits a maximum resolution greater than what is required by specification. This improved resolution causes B to be smaller, and consequently, the HFD to be longer.

Calculating DOF_N and DOF_F for a particular focus distance, f_d, could easily be done for the F4949 given the information in the previous paragraph. However, it would be more useful to examine what the equations do as a function of f_d. When the location of the DOF_N and the DOF_F are plotted as a function of the focus distance, the results are shown in Figure 4. This figure has two interesting features. First, as f_d gets very large, as it would when one focuses an imaging system at infinity, the near edge of the depth of field converges to the HFD. This is evident on Figure 4 because the plot of DOF_N becomes a horizontal line for large f_d. Also note that as f_d approaches the HFD, the plot of DOF_F rises very quickly. This indicates that the far edge goes to

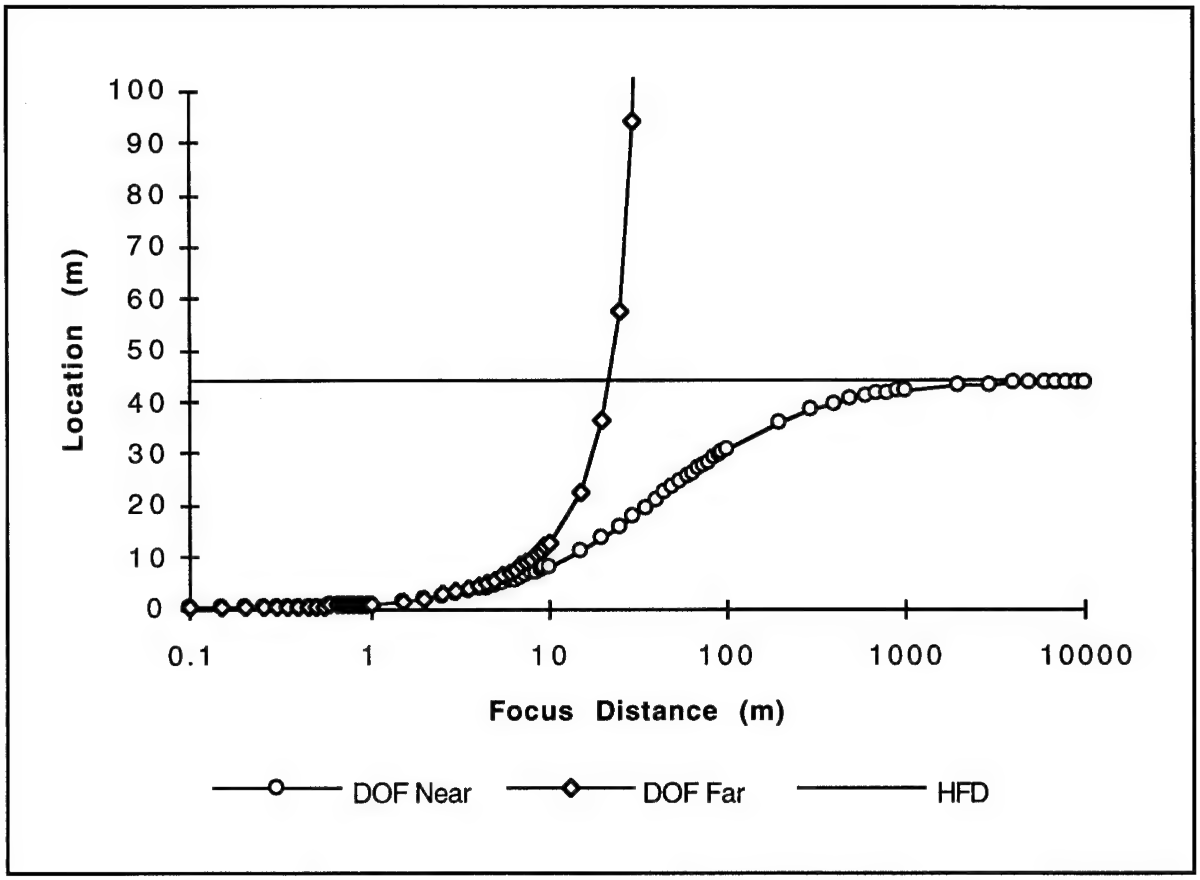

Figure 4. Near and far edges of depth of field vs. focus distance.

infinity when the device is focused at the HFD. As shown in Section 2, this is the condition of the greatest depth of field. Focusing farther out than the HFD decreases the depth of field because it moves the near edge away from the user. Unfortunately, focusing an NVD precisely at its HFD is a difficult, if not impossible, task. The current mechanisms for focusing NVD objective lenses do not provide the positioning accuracy required.

One should note that Figure 4 is a plot of the two edges of the NVD depth of field, not the depth of field itself. Calculating the difference between DOF_N and DOF_F and plotting it as a function of focus distance, as in Figure 5, it is easier to see a trend. Note that for distances less than the HFD, the depth of field also gets larger as the distance at which the NVD is focused increases.

Figure 6 illustrates the effect of aperture size, D, on F4949 depth of field for several focus distances. Note that apertures above 10 mm have little effect but apertures below 5 mm show significant increases in depth of field. Also note that as focus distance gets longer, the curves move up and to the right, indicating that for longer focus distances, the user can achieve the same depth of field with a larger aperture. This effect gives rise to a significant tradeoff that will be

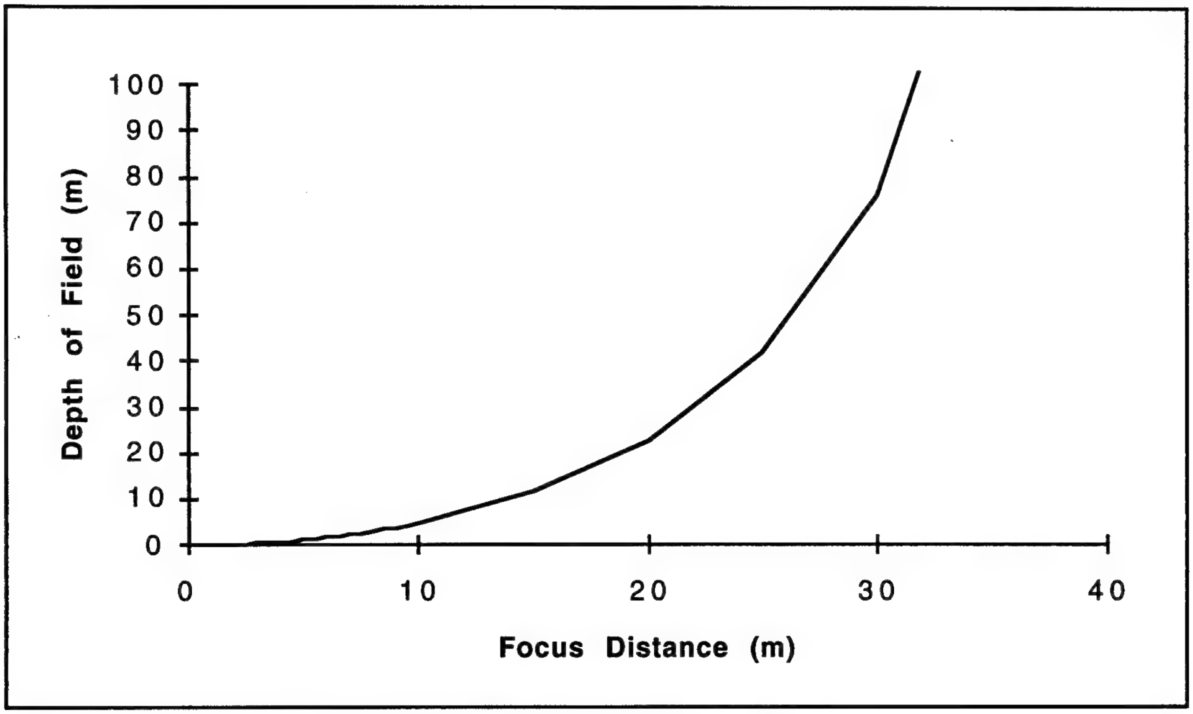

Figure 5. Depth of field vs. focus distance.

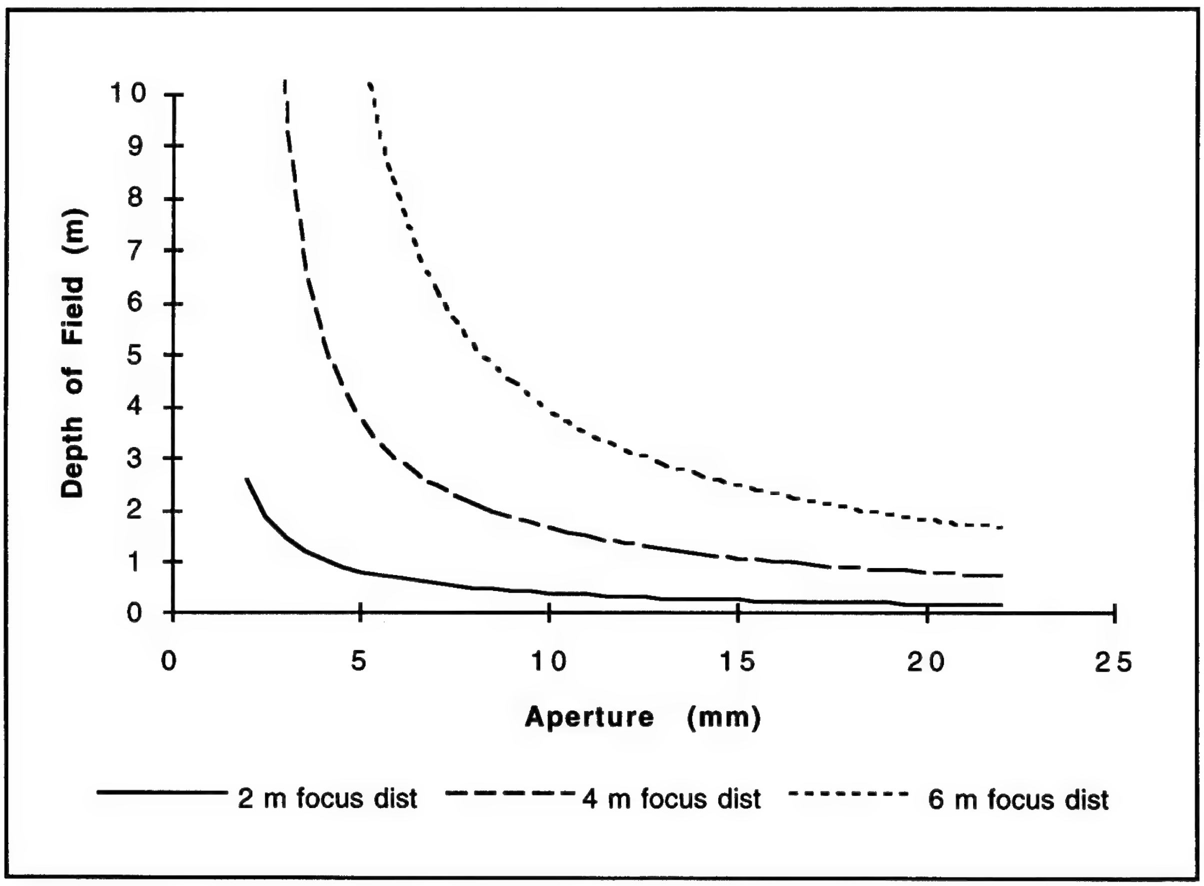

Figure 6. Depth of field vs. aperture size for various focus distances.

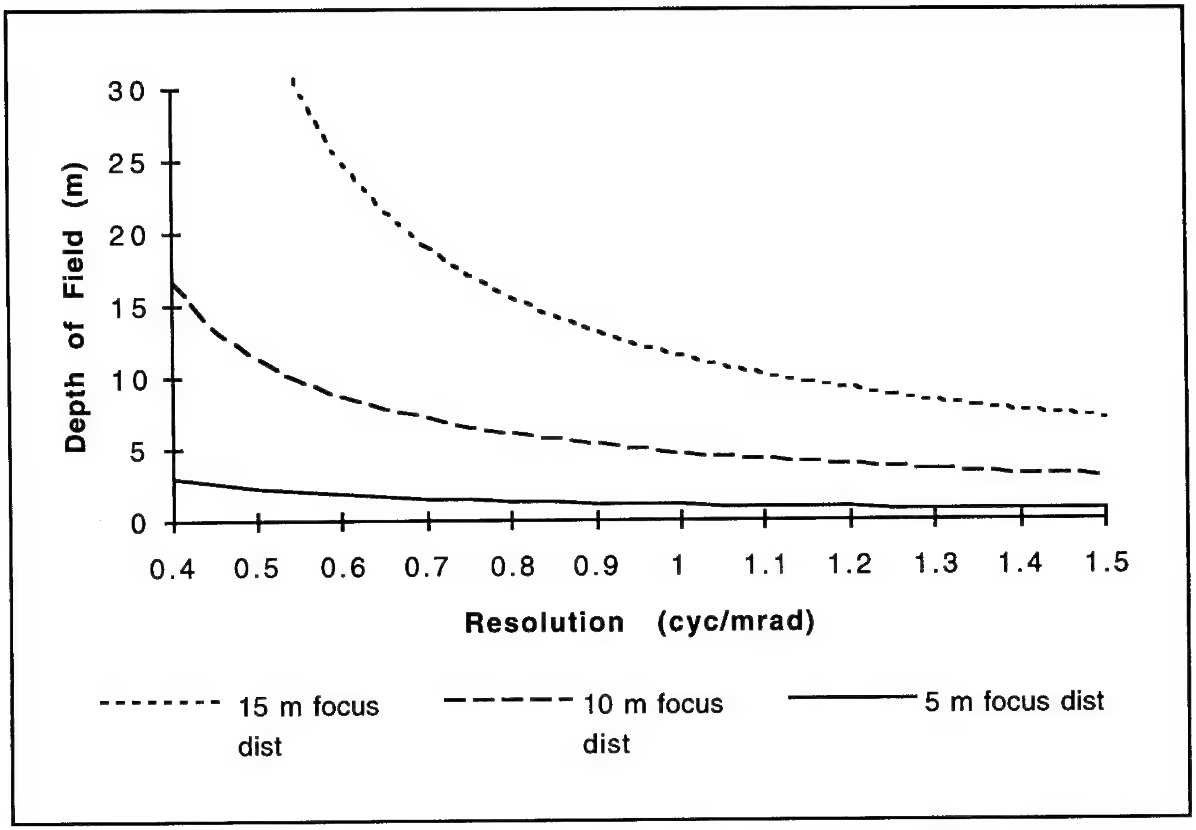

Figure 7. Depth of field vs. NVD resolution for various focus distances.

discussed later.

Figure 7 shows how depth of field changes with respect to NVD resolution performance for an ANVIS-type system, $f_o = 27.03$ mm, without a limiting aperture, D = 21.98 mm. The trend indicates that high resolution systems will have smaller depths of field. This is due to the pixel nature of I^2 tubes. To achieve higher resolution, the pixels, or rather the channels of the microchannel plate must be made smaller, making the overall system more susceptible to defocus or blur. It should be noted that, for the same reason, NVD HFD also increases. The simplest way around this effect, and recover the lost depth of field, is to shorten the objective lens focal length and decrease the objective lens diameter, thereby maintaining a constant f/#. Unfortunately, this would effectively increase the apparent angular size of the individual pixels and reduce the overall system resolution.

Another conclusion that can be drawn from Figure 7 is that depth of field is larger for low resolution NVDs. If the user is willing to accept a resolution performance loss, depth of field will appear larger. An NVD can process targets whose angular size is greater than or equal to the device's limiting resolution. If a user is trying to see large targets and adequate performance can be achieved with a somewhat blurred image (low resolution), user depth of field will appear to be larger. This is possible because in a blurrier image, B is allowed to be larger. Mathematically, a

larger B increases the difference between DOF_N and DOF_F and therefore yields a larger depth of field. However, if maximum resolution performance is required, the resulting depth of field will be small.

PROBLEMS

Radiometry of Small Apertures

As shown in Figure 6, it can be seen that depth of field increases dramatically as the limiting aperture diameter decreases. Unfortunately there is a tradeoff occurring at the same time. The light gathering capability of the device decreases as the limiting aperture gets smaller. When light is plentiful, this is not a problem. But in situations where one would normally use an NVD, light is scarce.

The radiometry of the problem is very straight forward and described by the following equation (Boyd, 1983):

$$\Phi = LA\Omega \tag{4.1}$$

In Equation 4.1, Φ is the radiant power or flux, L is the radiance of the source, A is the projected area of the detector, and Ω is the solid angle the source subtends from the point of view of the detector. The ratio of the radiant power collected by two different detectors is therefore given by:

$$\frac{\Phi_1}{\Phi_2} = \frac{L_1 A_1 \Omega_1}{L_2 A_2 \Omega_2} \tag{4.2}$$

In this case, it will be assumed that the two detectors are NVDs looking at the same scene, from the same point in space, but with different size apertures over their objective lenses. That means that they both see the same scene radiance, $L_1 = L_2 = L$, and solid angle, $\Omega_1 = \Omega_2 = \Omega$. This simplifies Equation 4.2 to:

$$\frac{\Phi_1}{\Phi_2} = \frac{LA_1\Omega}{LA_2\Omega} = \frac{A_1}{A_2} \tag{4.3}$$

In radiometry, when a lens is involved, the area of the detector becomes the area of the collecting lens (Boyd, 1983). A_1 and A_2 now represent the areas of the two objective lens apertures. Therefore, Equation 4.3 can be simplified even further, given that r is the radius of a particular aperture:

$$\frac{\Phi_1}{\Phi_2} = \frac{A_1}{A_2} = \frac{\pi r_1^2}{\pi r_2^2} = \frac{r_1^2}{r_2^2} \tag{4.4}$$

Therefore, when using small apertures to increase depth of focus, device light gathering capability is reduced by the ratio of the squares of the radii of the apertures involved. In other words, the light gathering capability can be expressed as a fraction of the light normally seen by the NVD. This fraction is the square of the radius of the limiting aperture divided by the square of the normal NVD objective lens radius. Mathematically this can be expressed:

$$\text{Fraction of available light reaching NVD} = \frac{(\text{radius of aperture})^2}{(\text{radius of lens})^2} \tag{4.5}$$

As a percentage, it can be expressed:

$$\text{\% of available light reaching NVD} = \frac{(\text{radius of aperture})^2}{(\text{radius of lens})^2} \text{ X } 100\% \tag{4.6}$$

For example, if a 3 mm aperture is placed over a 23.5 mm NVD objective lens, the NVD will only see 1.70% of the available light. Note that these calculations are made using the physical size of the NVD objective lens aperture and not D, the exit pupil diameter, as in earlier calculations. The radiometry would not correctly describe the phenomenon if D was used here.

This indicates that operations with small apertures over NVD objectives may require the use of bright auxiliary light sources. If such sources are not infrared, then the user may find it easier to simply take their NVD off and turn on ordinary lights.

Diffraction Limit

Even if adequate light is available for conducting NVD operations with very small apertures to increase depth of field, there is another limit that cannot be overcome: the objective lens diffraction limit. It is possible to try to operate with an aperture on a NVD that is small enough to create a diffraction spot larger than the limiting resolution of the I^2 tube. When this happens, the benefit of the larger depth of field is significantly reduced by the loss of system resolution. Physical optics theory indicates that the diffraction limited spot size, in microns, of an optical system is give by (Smith, 1990):

$$\text{Spot Size} = 2.44\ \lambda\ f/\# \tag{4.7}$$

where λ is the wavelength of light, expressed in microns.

Note that ANVIS-type NVDs, such as the F4949, are equipped with a minus-blue filter to shape the I^2 tube photocathode response and block most visible light. These filters pass light at

numerous wavelengths. Approximating the filter response to a single wavelength can be done by averaging the cut-on wavelength, 0.625 µm for Class A filters, 0.665 µm for Class B filtered goggles, and the cut-off wavelength of the photocathode, approximately 0.900 µm for the third generation I^2 tube's photocathode (MIL-L-85762A). This yields average wavelengths of 0.763 µm for Class A filters and 0.783 µm for Class B filters. A third minus-blue filter, the "Leaky Green" filter, which transmits a small amount of green light, is slowly becoming available. However, this green transmittance can be ignored for approximating an average wavelength because its intensity is low when compared with the transmitted infrared light. The wavelength of green light is also significantly shorter than the infrared wavelengths which dominate the phenomenon. A diffraction spot from green light will be smaller than the one caused by the accompanying infrared and therefore will go unnoticed.

Remembering that f/# can be expressed:

$$f/\# = \frac{f_o}{D} \tag{4.8}$$

The spot size equation can be rewritten:

$$\text{Spot Size} = \frac{2.44\lambda f_o}{D} \tag{4.9}$$

Note that as the aperture becomes smaller, the diffraction limited spot size becomes larger, as plotted in Figure 9. When the aperture is small enough, the diffraction limited spot size becomes equal to or greater than the resolution limit of the I^2 tube. When this happens, the maximum resolution of the device becomes equal to the diffraction spot size, decreasing resolution of the NVD and reducing the benefit of a large depth of field. For an F4949 type system, this happens when the lens limiting aperture shrinks below 3.7 mm with a Class A filtered response, and below 3.8 mm with a Class B filtered response. However, because of the energy distribution of the diffraction spot, this phenomenon will not become significant until apertures about half as large as the calculated values are employed. (Smith, 1990)

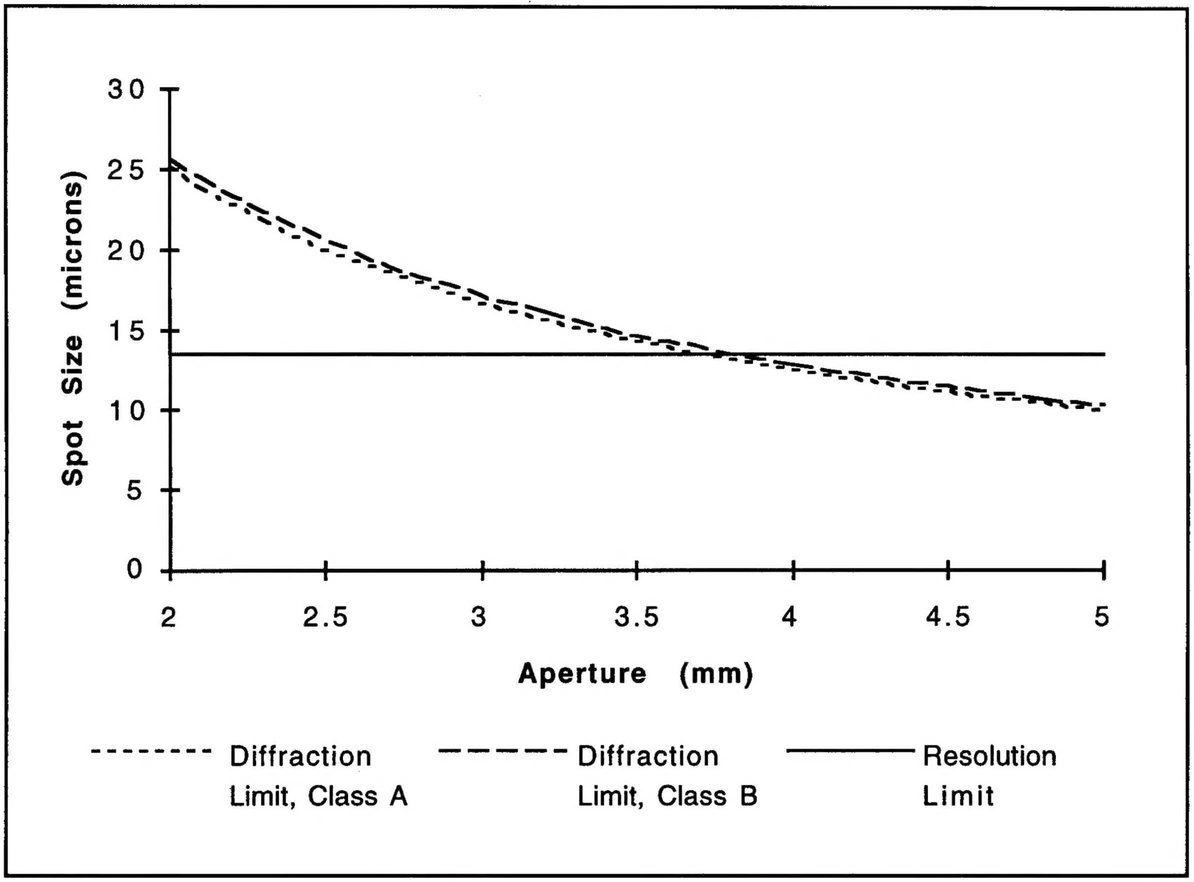

Figure 8. Diffraction limited spot size vs. aperture diameter.

CONCLUSIONS

The depth of field of imaging systems like NVDs is influenced by objective lens focal length, objective lens diameter, system resolution, and focus distance. Adjusting any of these parameters will have a noticeable effect on device depth of field. Adding apertures to reduce the objective lens diameter can significantly increase NVD depth of field. The amount of improvement required in an application is largely determined by the image quality the user desires.

Several physical limitations exist which must be balanced through tradeoffs limiting the usefulness of the small aperture approach to increasing depth of field. It is possible to reach the diffraction limit of the objective lens and aperture combination and degrade NVD resolution performance for very slow f/#'s. Adding apertures to achieve this greater depth of field dramatically reduces the light gathering capability of the device. Supplemental illumination, such as powerful auxiliary infrared illuminators, may be necessary to achieve the desired system performance.

Other parameters can be adjusted to increase NVD depth of field. Accepting lower system resolution performance will make device depth of field appear larger. This may be difficult for some users whose duties require high resolution NVDs to accept (Donohue-Perry, et. al., 1993). Shortening the objective lens focal length while maintaining objective lens f/# will lead to a larger depth of field but will reduce the system's overall resolution performance. Implementing this option would require the complete redesign of the device objective lens; an expensive and lengthy undertaking. Objective lens focus distance can be optimized to yield a greater depth of field by focusing at the device's HFD. However, this is only practical when infinity focus is required. Poor objective lens positioning mechanisms make this approach difficult to implement.

This report examines the theoretical effects of placing apertures over an NVD objective lens. Some performance characteristics can be sacrificed or traded to optimize NVD depth of field. These tradeoffs must be examined on the basis of individual situations or applications to determine the most acceptable compromise between depth of field, resolution performance, and light gathering before this idea can be implemented.

BIBLIOGRAPHY

Boyd, R.W. (1983). *Radiometry and the detection of optical radiation.* New York: John Wiley & Sons.

Csorba, I.P. (1985). *Image tubes.* Indianapolis: Howard W. Sams & Co., Inc.

Donohue-Perry, M.M., Hettinger, L.J., Riegler, J.T., & Davis, S.D. (1993). *Night vision goggle users' concerns survey site report: Dover AFB, DE,* (Report No. AL/CF-TR-1993-0075). Wright-Patterson AFB, OH: Armstrong Laboratory.

Donohue-Perry, M.M., Hettinger, L.J., & Riegler, J.T. (1992). *Night vision goggle users' concerns survey site report: Hurlburt Field, FL,* (Report No. AL-TR-1992-0089). Wright-Patterson AFB, OH: Armstrong Laboratory. (DTIC No. B171286)

Jenkins, J. A., White, W. E. (1976). *Fundamentals of optics.* New York: McGraw-Hill Book Co.

Military Specification, *Lighting, Aircraft, Interior, Night Vision Imaging System (NVIS) Compatible*, MIL-L-85762A.

Military Specification, *Lens Assembly, Objective for Aviator's Night Vision Imaging System ANAVS-6(V)1, AN/AVS-6(V)2*, MIL-I-49426(CR).

Military Specification, *Image Intensifier Assembly, 18mm Microchannel Wafer, MX-10160/AVS-6*, MIL-I-49428(CR).

Smith, W. S. (1990). *Modern optical engineering - the design of optical systems.* New York: McGraw-Hill, Inc.

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